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(71) Applicant: HRL LABORATORIES, LLC [US/US]; 3011 Malibu Canyon Road, Malibu, CA 90265-4799 (US).

(72) Inventors: SIEVENPIPER, Daniel; 11300 Exposition Blvd. #215, Los Angeles, CA 90064 (US). HARVEY, Robin, J.; 809 La Grange Ave., Newbury Park, CA 91320 (US). TANGONAN, Greg; 141 Santa Rosa Avenue, Oxnard, CA 93035 (US). LOO, Robert, Y.; 29046 Old Carriage Court, Agoura Hills, CA 91301 (US). SCHAFFNER, James, H.; 9960 Owensmouth Avenue #8, Chatsworth, CA 91311 (US).

(74) Agents: BERG, Richard, P. et al.; Ladas & Parry, Suite 2100, 5670 Wilshire Blvd., Los Angeles, CA 90036 (US).

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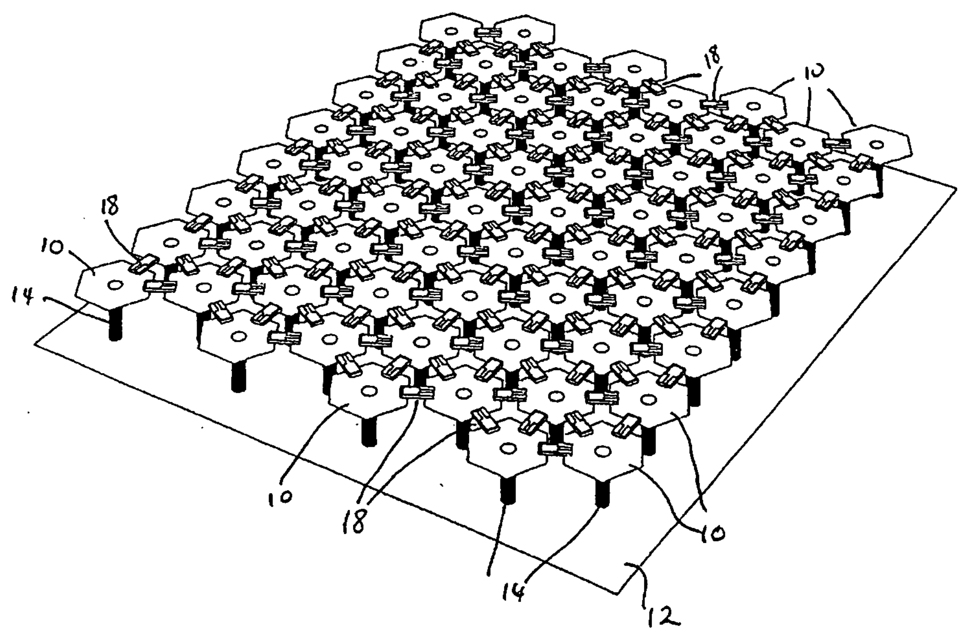
(54) Title: A TUNABLE IMPEDANCE SURFACE



(57) Abstract: A tuneable impedance surface for steering and/or focusing a radio frequency beam. The tunablesurface comprises a ground plane; a first plurality of elements disposed in an array a firstdistance from the ground plane, the distance being less than a wavelength of the radio frequencybeam; and a second plurality of elements disposed in an array for controlling the capacitance between the elements of the first array. The second plurality of elements include, in one embodiment, variable discrete capacitors and, in another embodiment, a plurality of platesarranged to be moveable relative to the first plurality of elements.

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A Tunable Impedance Surface

Technical Field

This invention relates to a surface having a tunable electromagnetic impedance which acts as a reconfigurable beam steering reflector.

Background of the Invention

Steerable antennas today are found in two common configurations: those with a single feed or reflector that is mechanically steered using a gimbals, and those with a stationary array of electronically phased radiating elements. Both have shortcomings, and the choice of system used is often a tradeoff between cost, speed, reliability, and RF (radio frequency) performance. Mechanically steered antennas are inexpensive, but moving parts can be slow and unreliable, and they can require an unnecessarily large volume of unobstructed free space for movement. Active phased arrays are faster and more reliable, but they are much more expensive, and can suffer from significant losses due to the complex feed structure required to supply the RF signal to and/or receive the RF signal from each active element of the phased array. Losses can be mitigated if an amplifier is included in each element or subarray, but this solution contributes to noise and power consumption and further increases the cost of the antenna.

One alternative is to use a reflectarray geometry, and replace the lossy corporate feed network with a free space feed. The actively phased elements operate in reflection mode, and are illuminated by a single feed antenna. The array steers the RF beam by forming an effective reflection surface defined by the gradient of the reflection phase across the array. Using current techniques, such a system still requires a large number of expensive phase shifters.

There is a need for a reflective surface, in which the reflection phase could be arbitrarily defined, and easily varied as a function of position. The surface should be less expensive than a comparably sized array of conventional phase shifters, yet hopefully offer similar RF performance. Such a surface could behave as a generic reconfigurable reflector, with the ability to perform a variety of important functions including steering or focusing of one or more RF beams. It is the object of this invention to fulfill this need.

The reconfigurable reflector disclosed herein is based a resonant textured ground plane, often known as the high-impedance surface or simply the Hi-Z surface. This electromagnetic structure has two important RF properties that are applicable to low profile antennas. It suppresses propagating surface currents, which improves the radiation pattern of antennas on finite ground planes and it provides a high-impedance boundary condition, acting as an artificial magnetic conductor, which allows radiating elements to lie in close proximity to the ground plane without being shorted out. It has origins in other well-known electromagnetic structures such as the corrugated surface and the photonic band gap surface. A prior art high-impedance surface is disclosed in a pending US patent application of D. Sievenpiper, E. Yablonovitch, "Circuit and Method for Eliminating Surface Currents on Metals", PCT application PCT/US99/06884, published 7 October 1999 as WO 99/50929.

A prior art high-impedance surface is shown in Figure 1. It consists of an array of metal top plates or elements 10 on a flat metal sheet 12. It can be fabricated using printed circuit board technology with the metal plates or elements 10 formed on a top or first surface of a printed circuit board and a solid conducting ground or back plane 12 formed on a bottom or second surface of the printed circuit board. Vertical connections are formed as metal plated vias 14 in the printed circuit board, which connect the elements 10 with the underlying ground plane 12. The metal members, comprising the top plates 10 and the vias 14, are arranged in a two-dimensional lattice of cells or cavities, and can be visualized as mushroom-shaped or thumbtack-shaped members protruding from the flat metal surface 12. The thickness of the structure, which is controlled by the thickness of the printed circuit board, is much less than one wavelength for the frequencies of interest. The sizes of the elements 10 are also kept less than one wavelength for the frequencies of interest. The printed circuit board is not shown for ease of illustration.

Turning to Figure 2, the properties of this surface can be explained using an effective circuit model or cavity which is assigned a surface impedance equal to that of a parallel resonant LC circuit. The use of lumped cavities to describe electromagnetic structures is valid when the wavelength is much longer than the size of the individual features, as is the case here. When an electromagnetic wave interacts with the surface of Figure 1, it causes charges to build up on the ends of the top metal plates 10. This process can be described as governed by an effective capacitance C. As the charges slosh back and forth, in response to a radio-frequency field, they flow around a long path P through the vias 14 and the bottom metal surface 12. Associated with these currents is a magnetic field, and thus an inductance L. The capacitance C is controlled by the proximity of the adjacent metal plates 10 while the inductance L is controlled by the thickness of the structure.

The structure is inductive below the resonance and capacitive above resonance. Near its resonance frequency, $\omega = \frac{1}{\sqrt{LC}}$, the structure exhibits high electromagnetic surface impedance. The tangential electric field at the surface is finite, while the tangential magnetic field is zero. Thus, electromagnetic waves are reflected without the phase reversal that occurs on a flat metal sheet. In general, the reflection phase can be 0, π, or anything in between, depending on the relationship between the test frequency and the resonance frequency of the structure. The reflection phase as a function of frequency, calculated using the effective medium model, is shown in Figure 3. Far below resonance, it behaves like an ordinary metal surface, and reflects with a π phase shift. Near resonance, where the surface impedance is high, the reflection phase crosses through zero. At higher frequencies, the phase approaches $-\pi$. The calculated model of Figure 3 is supported by the measured reflection phase, shown for an example structure in Figure 4.

A large number of structures of the type shown in Figure 1 have been fabricated with a wide range of resonance frequencies, including various geometries and substrate materials. Some of the structure were designed with overlapping capacitor plates, to increase the capacitance and lower the frequency. The measured and calculated resonance frequencies for twenty three structures with various capacitance values are compared in Figure 5. Clearly, the resonance frequency is a predictable function of the capacitance. The dotted line in Figure 5 has a slope of unity, and indicates perfect agreement. The bars indicate the instantaneous bandwidth of the surface, defined by the frequencies where the phase is between $\pi/2$ and $-\pi/2$.

For a more detailed description and analysis of the high-impedance surface, see D. Sievenpiper, L. Zhang, R. Broas, N. Alexopolous, E. Yablonovitch, "High-Impedance Electromagnetic Surfaces with a Forbidden Frequency Band", IEEE Transactions on Microwave Theory and Techniques, vol. 47, pp. 2059-2074, 1999 and D. Sievenpiper, "High-Impedance Electromagnetic Surfaces", Ph.D. dissertation, Department of Electrical Engineering, University of California, Los Angeles, CA, 1999

When the resonant cavities are much smaller than the wavelength of interest, the electromagnetic analysis can be simplified by considering them as lumped LC circuits. The proximity of the neighboring metal plates provides capacitance, while the conductive path that connects them provides inductance. The textured ground plane supports an electromagnetic boundary condition that can be characterized by the impedance of an effective parallel LC circuit, given by

$Z_s = \dfrac{j\omega L}{1-\omega^2 LC}$, The sheet inductance is $L=\mu t$, where μ is the magnetic permeability of the circuit board material, and t is its thickness. For a structure with parallel plate capacitors arranged on a square lattice, the sheet capacitance is $C=\varepsilon A/d$, where ε is the electric permitivity of the dielectric insulator, and A and d are the overlap area and separation, respectively, of the metal plates

The surface has a frequency-dependent reflection phase given by

$$\Phi = \mathrm{Im}\left\{ Ln\left(\frac{Z_s-\eta}{Z_s+\eta}\right)\right\}$$

where η is the impedance of free space. Far from the resonance frequency, the surface behaves as an ordinary electric conductor, and reflects with a π phase shift. Near the resonance frequency, the cavities interact strongly with the incoming waves. The surface supports a finite tangential electric field across the lattice of capacitors, and the structure has high, yet reactive surface impedance. At resonance, it reflects with zero phase shift, providing the effective boundary condition of an artificial magnetic conductor. Scanning through the resonance condition from low to high frequencies, the reflection phase varies from π, to zero, to $-\pi$. Thus, by tuning the resonance frequency of the cavities, one can tune the reflection phase of the surface for a fixed frequency.

This tunable reflection phase is the basis of the reconfigurable beam steering reflector disclosed herein. By varying the reflection phase as a function of position across the surface, one can perform a variety of functions. For example, a linear phase gradient is equivalent to a virtual tilt of the reflector. A saw-tooth phase function transforms the surface into a virtual grating. A parabolic phase function can focus a plane wave onto a small feed horn, allowing the flat surface to replace a parabolic dish.

Brief Description of the Invention

Features of the present invention include:

1. A tunable surface impedance;
2. A method of making a tunable impedance surface;

2. A method for focusing an electromagnetic wave using the tunable surface; and
3. A method for steering an electromagnetic wave using the tunable surface.

This invention provides a reconfigurable electromagnetic surface which is capable of performing a variety of functions, such as focusing or steering a beam. It improves upon the high-impedance surface, which is the subject of PCT application PCT/US99/06884, published 7 October 1999 as WO 99/50929, to include the important aspect of tunability.

The present invention provides a tuneable impedance surface for steering and/or focusing a radio frequency beam. The tunable surface comprises a ground plane; a first plurality of elements disposed in an array a first distance from the ground plane, the distance being less than a wavelength of the radio frequency beam; and a second plurality of elements disposed in an array for controlling the capacitance between the elements of the first array. The second plurality of elements include, in one embodiment, variable discrete capacitors and, in another embodiment, a plurality of plates arranged to be moveable relative to the first plurality of elements.

The present invention provides, in another aspect, a tuneable impedance surface for steering and/or focusing a radio frequency beam, the tunable surface comprising: a ground plane; a first plurality of top plates disposed a distance from the ground plane, the distance being less than a wavelength of the radio frequency beam; and a second plurality of top plates disposed a different distance from the ground plane, the second plurality being moveable relative to the first plurality.

Brief Description of the Drawings

Figure 1 depicts a conventional high-impedance surface fabricated using printed circuit board technology of the type disclosed in U.S. Provisional Patent Serial Number 60/079,953 and having metal plates on the top side connect through metal plated vias to a solid metal ground plan on the bottom side;

Figure 2 is a circuit equivalent of a pair of adjacent metal top plates and associated vias;

Figure 3 depicts the calculated reflection phase of the high-impedance surface, obtained from the effective medium model and shows that the phase crosses through zero at the resonance frequency of the structure;

Figure 4 shows that the measured reflection phase agrees well with the calculated reflection phase;

Figure 5 depicts the measured resonance frequency compared to the calculated resonance frequency, using the effective circuit model of Figure 2, for twenty three examples of the surface shown in Figure 1;

Figure 6 depicts a high impedance surface with an array of variable capacitors placed between neighboring top plates;

Figure 7 depicts a circuit equivalent of the surface shown by Figure 6, modified so that the addressing of each variable capacitor occurs by applying a voltage through an associated conducting via;

Figure 8 depicts a top view of one embodiment of the present invention

Figure 9 depicts a top view of another embodiment of the present invention;

Figure 9a depicts a top view of one embodiment of the present invention similar to that of Figure 9, but with all elements being controllable;

Figure 10 depicts a top view of yet another embodiment of the present invention;

Figure 10a depicts a top view of one embodiment of the present invention similar to that of Figure 10, but with all elements being controllable;

Figure 11 depicts another technique for tuning the capacitance by using heaters arranged below the surface, which heaters causing bimetallic strips on the top surface to bend;

Figure 12 demonstrates how beam can be steered by impressing a linear reflection phase function on the tunable impedance surface - phase discontinuities of 2π are used to steer to large angles, making the surface resemble a grating;

Figure 13 demonstrates how a parabolic reflection phase function can be used to focus a beam;

Figures 14a and 14b depict a pair of printed circuit boards, in side elevation and plan views, one

board of which is a high-impedance surface while the second board is slidable relative to the high-impedance surface and includes an array of conductive plates or patches which overlap the plates or patches of the high-impedance surface;

Figure 15 depicts a circuit topology corresponding to Figures 14 a and 14b showing how the change in capacitance depends on the polarization of an incoming wave;

Figure 16 is a somewhat more detailed version of Figure 14a, showing the two boards contacting each other and showing the effect of movement of one board relative to the other in terms of capacitance changes;

Figure 17 is a graph of the measured reflection phase of the experimental structure shown in Figures 14a and 14b as a function of frequency for ten different positions of the one board, displaced in the direction of the applied electric field relative to the other board;

Figure 18 shows rotation of one board relative to the other in order to vary the resonance frequency and thus the reflection phase, as a function of position, of the tunable surface so that it can be used to steer a reflected beam;

Figure 19 is a graph of the measured reflection magnitude as a function of incidence angle with the two boards aligned with each other;

Figures 20a and 20b are graphs of the measured reflection magnitude as a function of incidence angle with for two different relative orientations of the two boards;

Figure 21 demonstrates a test of the microwave grating having two periods in which the movable board of the experimental structure was physically divided down its center into two portions were offset as shown in this figure;

Figures 22a and 22b are graphs of the measured reflection magnitude as a function of incidence angle with for two different relative orientations of the two boards when set up to have two periods as shown in Figure 21;

Figure 23 is a graph of phase discontinuities which can occur with movement or rotation of the one of the board relative to the other board; and

Figure 24 depicts two boards, one with conductive patches of a uniform size and arrangement

and the other of a uniform size but a non-uniform arrangement.

I. Detailed Description of a first Embodiment

In accordance with a first embodiment of the present invention, a high-impedance surface 16 is modified by adding variable capacitors 18 as illustrated in Figure 6. These variable capacitors 18 can take a variety of forms, including microelectomechanical capacitors, plunger-type actuators, thermally activated bimetallic plates, or any other device for effectively varying the capacitance between a pair of capacitor plates 10. The variable capacitors 18 can alternatively be solid state devices, in which a ferroelectric or semiconductor material provides a variable capacitance controlled by an externally applied voltage. An example is shown in Figure 6, where individual variable capacitors 18 are disposed between each neighboring pair of hexagonal metallic top plate elements 10. By changing the capacitance, the curves in Figures 3 and 4 are shifted according to the resonance frequency given by the relation: $\omega = \frac{1}{\sqrt{LC}}$ as verified by the data depicted in Figure 5. This has the effect of changing the impedance at a single frequency. By varying the capacitance as a function of distance along (or location on) the surface, a position-dependent or location-dependent impedance can be generated on the surface 30 (Figures 6 and 7), and thus a position-dependent or location-dependent reflection phase occurs. A tunable high-impedance surface 30 is thus provided.

The variable capacitors 18 can be provided by microelectromechanical capacitors, thermally activated bimetallic strips, plungers, or any other device for moving a capacitor plate. Alternatively, elements 18 could be semiconductor or ferroelectric variacs.

The capacitance C of a cell of the high impedance surface can be less than 1 pF. As such the amount of capacitance to be added to each cell to change the impedance can also be quite small and therefor the physical size of elements 18 can likewise be small. Indeed, elements 18 adding capacitance in the range of 0.1 to 1.0 pF per cell will often be quite suitable.

The tunable surface of Figure 6 is preferably built or disposed on a substrate 24 (Figure 7) such as a printed circuit board. The thickness of the printed circuit board is kept preferably much less than the wavelength associated with the frequency or frequency band of interest. For high frequency applications, that means than the printed circuit board is rather thin. Thin printed circuit boards having a thickness of only 0.1 mm are readily available For example, polyimide

printed circuit boards are commercially available as thin as 1 mil (0.025 mm) and therefore the disclosed structure with printed circuit board technology can be used in very high frequency applications, if desired. The elements 10 are electrically conductive and typically made of a metal conveniently used in printed circuit board fabrication processes and are disposed on one surface of the substrate 24. The back plane 12 is disposed on the opposite surface of substrate 24. Vias are typically provided and plated to form conductors 14. Conductors 14 are connected to the elements 10 at one end thereof and are coupled, either capacitively or directly, as will be discussed later, at or near another end thereof to the back plane 12.

Elements 10 should be sized to be less than one half the wavelength associated with the frequency of interest. However, to minimize sidelobes, the performance of the high-impedance surface will improve as the cell size is reduced, i.e. as the physical size of the elements 10 is reduced. Preferably, the size of the elements 10 is kept to less than one tenth the wavelength associated with the frequency of interest, since that yields good results while keeping the high impedance surface reasonably manufacturable.

If elements 18 are provided by microelectromechanical capacitors, or by solid state variacs, the capacitance can be changed by changing an applied voltage, which can be routed through the conductive vias 14. This can be accomplished by dividing the array of elements 10 into two subsets: 10a and 10b. One subset 10a is electrically grounded, while the second subset 10b would have an applied control voltage that may be different for each element in subset 10b. The control voltage is applied through a via 14b, which in this case would not be connected to the ground plane 12, but instead to an external data bus 20. This embodiment is illustrated by Figure 7. The data lines 20 are fed to an external control unit (not shown) for generating the desired control voltages for various beam steering or focusing operations. In this embodiment, the data lines 20 each preferably include an RF choke (not shown) wired in series to prevent radiation to the back side.

Additionally, the vias 14b are capacitively coupled to the ground plane 12 so that they appear to be connected to the ground plane 12 at the RF frequencies of interest, but not at the much lower frequencies of the control voltages (which would typically be considered to be comparatively slowly changing DC voltages). Since the vias 14b conveniently pass through the ground plane 12, they are conveniently capacitively coupled to the ground plane 12 where they penetrate the ground plane 12 and that capacitance at that point 14c can be conveniently controlled using techniques well known in the art. Preferably, the capacitance at the penetration point 14c is much larger than the capacitance of elements 18.

Figure 8 shows an embodiment of an hexagonal array of elements 10 a and 10b. Recall that elements 10a are directly connected to the ground plane while elements 10b are connected to control voltages (but are capacitively or effectively coupled to the ground plane for the frequencies of the impinging RF waves of interest). The capacitances added by elements 18 are controlled by the control voltages on bus 20. Considering some particular elements 10 identified by the letters A, B, and C in Figure 8, it will be noted that element A is directly coupled to ground since it is a member of subset 10a, while elements B and C have control voltages applied thereto as they both belong to subset 10b. The element 18 between elements A and B is controlled by the control voltage applied to element B through its associated via 14b. The capacitance between elements A and B is controlled by (i) their physical relationship and (ii) the capacitance contributed by the aforementioned element 18. Likewise, the element 18 between elements A and C is controlled by the control voltage applied to element C through its associated via 14b. However, the capacitance between elements B and C is fixed in this embodiment by their physical relationship. Of course, an element 18 could be provided between elements B and C in which case the capacitance contributed by that added element 18 would be based on the difference of the control voltages applied to elements B and C. Those skilled in the art will appreciate that such control based on voltage differences adds additional complication, since the added capacitances provided by at least some of the elements 18 are then a function of the differences in the control voltages. But if that added complication is warranted in order to provide greater control of the impedance of the surface, then even more (or perhaps all) of the elements 10 could be controlled by control voltages (in which case less or none of the elements would be directly grounded as in the case of subset 10a). As can be seen, the ratio of controlled (subset 10b) to uncontrolled (subset 10a) elements 10 can vary greatly.

Alternatively, all of the elements 10 can be directly connected to ground plane 12 and the control voltages from bus 20 can be connected directly to the various variable capacitors 18 through other vias (not shown), in which case no element 10 would be a controlled element of subset 10b.

Figure 9 shows an embodiment of a rectangular arrangement of the elements 10a and 10b. The ratio of controlled (subset 10b) to uncontrolled (subset 10a) elements in this figure is shown as being 1:1 and an element 18 is disposed between each element 10. However, if all of the elements 18 are controlled and therefore all belong to subset 10b (no 10a elements), then the embodiment shown in Figure 9a is arrived at. Again, the ratio of controlled (subset 10b) to uncontrolled (subset 10a) elements 10 can vary greatly.

Figure 10 shows an embodiment of a triangular arrangement of the elements 10a and 10b. The

ratio of controlled (subset 10b) to uncontrolled (subset 10a) elements in this figure is shown as being 1:1 and an element 18 is disposed by between each element 10. However, if all of the elements 18 were controlled by making them subset 10b elements (in which case subset 10a is of a zero size), then the embodiment shown in Figure 10a is arrived at. As previously mentioned, the ratio of controlled (subset 10b) to uncontrolled (subset 10a) elements 10 can vary greatly.

The ratio of controlled (subset 10b) to uncontrolled (subset 10a) elements 10 can be less than 1:1, if desired, which will also have the effect of reducing the number of capacitor elements 18 utilized, but, of course, with less control of the impedance of the surface. However, that could be quite suitable in certain embodiments.

As an alternative method of tuning the capacitance, heaters 26 (Figure 11) can be arranged below the surface, which would actuate an array of bimetallic strips 18, which would bend according to the local temperature. This embodiment is shown by Figure 11 where heaters 26 are provided to control the position of the adjacent bimetallic strips 18. As the metallic strips 18 move to a close position, the capacitance increases. Another method of tuning the capacitance involves mechanical plungers, which could be moved by hydraulic pressure or by a series of magnetic coils. The examples given here are not meant to limit how additional capacitance can be added. Other techniques for tuning the capacitance may be utilized.

The operations that can be performed depend on the surface impedance, and thus the reflection phase, as a function of position. If the reflection phase assumes a linear slope 44, the surface can be used to steer an RF beam 32, as illustrated in Figure 12. Figure 12 demonstrates how incident beam 32 can be steered to produce a reflected beam 34 by impressing a linear reflection phase function 44 on the tunable impedance surface 30. To steer to large angles, phase discontinuities of 2π can be included, so the surface acts like a diffraction grating. Of course, the incident wave 32 can arrive at an angle other than 90 degrees to the surface 30 and the reflected wave can be reflected 90 degrees to the surface 30, if desired.

Alternatively, a parabolic function 46 can be used to focus a reflected beam 36, as shown in Figure 13. Figure 13 demonstrates how an incident RF beam 32 can be steered by impressing a parabolic reflection phase function 46 on the tunable impedance surface 30. To steer to large angles, phase discontinuities of 2π are included, so the surface acts like a Fresnel or parabolic reflector to focus an incident wave 32. The reflected beam may be focussed, for example, on a Low Noise Amplifier (LNA) of the type used with dish antennas. Here the reflecting surface 30 may be flat and moreover it is tunable to effective steer the antenna.

Of course, the tunable impedance surface 30 can be easily tuned by adjusting the capacitors 18 so that the impedance of the surface 30 varies as a function of location across the surface. As can be seen by reference to Figures 12 and 13, changing the impedance profile on the tunable impedance surface 30 has a profound effect on how an incident RF wave 32 interacts with the surface 30. Indeed, surface 30 can be planar and yet act as if it were a prior art parabolic dish reflector or a diffraction grating. Even more remarkable is the fact that surface 30 can be effectively programmed to mimic not only parabolic reflectors of different sizes, but also flat, angled reflectors or any other shape of reflector or diffraction grating by simply changing the impedance of the surface as a function of location on the surface.

In the embodiments shown by the drawings the tunable impedance surface 30 is depicted as being planar. However, this first embodiment of the invention is not limited to planar tunable impedance surfaces. Indeed, those skilled in the art will appreciate the fact that the printed circuit board technology preferably used to provide a substrate 24 for the tunable impedance surface 30 can provide a very flexible substrate 24. Thus the tunable impedance surface 30 can be mounted on any convenient surface and conform to the shape of that surface. The tuning of the impedance function would then be adjusted to account for the shape of that surface. Thus, surface 30 can be planar, non-planar, convex, concave or have any other shape and still act as if it were a prior art parabolic dish reflector or as a diffraction grating by appropriately tuning its surface impedance.

The top plate elements 10 and the ground or back plane element 12 are preferably formed from a metal such as copper or a copper alloy conveniently used in printed circuit board technologies. However, non-metallic, conductive materials may be used instead of metals for the top plate elements 10 and/or the ground or back plane element 12, if desired.

II. Detailed Description of a Second Embodiment

Figures 14a and 14b depict a tunable impedance surface in accordance with the present invention. Figure 14b is a plan view thereof while Figure14a provides a side elevation view thereof. The tunable impedance surface includes a pair of printed circuit boards 16, 18. The second board is given the same reference numeral, 18, as the variable capacitors of the first embodiment since it provides another means of tuning the capacitances of the conductive plate or patches 10 of the high impedance surface 16.

As in the case of the first embodiment, board 16 has a lattice of conductive structures10, 14 resembling the conventional high-impedance surface previously described. The back of this first board has a ground plane 12, preferably made of a thin, but solid, metal, and the front is covered with an array of conductive plates or patches 10 preferably made of metal, which are connected to the ground plane by conductive vias 14 preferably formed by plated metal. The conductive patches 10 and their associated conductive vias 14 form the conductive thumbtack-like structures. This structure can be easily fabricated, for example, on FR4, a standard fiberglass-based printed circuit material.

The second board 18 includes an array of conductive tuning plates or patches 20, preferably made of metal, which are designed to overlap the conductive patches 10 on the first board 16. The tuning patches 20 are supported on a sheet of FR4, and are preferably covered by an insulating layer 22 such as Kapton polyimide. The two boards may be pressed together with the conductive plates or patches 10, 20 separated by the polyimide insulator, forming a lattice of parallel plate capacitors. The confronting surfaces are designed to slide against each other, to allow adjustment of the overlap area between the matching sets of metal plates 10, 20, and thus allow the capacitors to be tuned. Indeed the confronting surface are preferably brought into close contact with each other as is even better depicted by Figure 16.

The two boards 16, 18 typically have a large number of conductive plates or patches 10, 20 formed thereon and the figures only show a small number of the plates or patches which would typically be formed for clarity of representation. In the experimental structure, which is discussed below, each board has approximately 1600 patches disposed thereon. The number of patches utilized is a matter of design choice.

a. An Experimental Structure

An experimental structure of this second embodiment of the invention has been made and tested. In the experimental structure, the plates 10, 20 were provided by square metal patches 10, 20 formed on both boards 16, 18 which measured 6.10 mm on each side and they were distributed on a 6.35 mm lattice. The fixed board 16 was 6.35 mm thick, and the conducting vias 14 were 500 μm in diameter, centered on the square metal plates 10. The movable board 18 was 1.57 mm thick, and the polyimide insulator 22 that covered the tuning plate was 50 μm thick. Both boards measured 25.4 cm on each edge. as such each board had an array of approximately 40 by 40 conducive patches 10, 20 thereon. To ensure uniform, intimate contact between the two matching surfaces, a vacuum pump was attached to the back of the fixed board. This evacuated the space between the boards by way of the hollow openings 15 preferably provided in the vias

14 and forced the two together.

By sliding the upper board 18 relative to the lower board 16, the overlap area of the capacitors is changed, tuning the resonance frequency of the small cavities on the surface. However, only movement that is parallel to the applied electric field contributes to a change in resonance frequency. This can be understood from the following discussion: The resonance frequency of the cavities is given by $\omega = \frac{1}{\sqrt{LC}}$, where C is the effective capacitance produced by a combination of four separate capacitors C_1-C_4 indicated in Figure 14b. The mode that is excited in the cavities, and the circuit topology that produces the effective capacitance, depends on the polarization of the incoming wave. The circuit topology for two cases is shown in Figure 15.

For example, consider an incoming wave polarized along direction Y, referring to Figure 14b for orientation. The effective capacitance is (C_1+C_2) in series with (C_3+C_4). If the top board 18 is moved in the +Y direction, parallel to the applied field, then C_1 and C_2 are increased while C_3 and C_4 are decreased by the same amount, as shown in Figure 16. Since the motion occurs along the direction of pairs of capacitors that are in series, the result is a net change in capacitance, and thus a change in resonance frequency. Conversely, if the top plate 18 is moved in the +X direction, perpendicular to the applied field, then C_2 and C_4 are increased while C_1 and C_3 are decreased by the same amount. Since the motion occurs along the direction of pairs that are in parallel, there is no net change in capacitance, and no change in resonance frequency. The maximum effective capacitance, and thus the lowest resonance frequency, occurs when the upper plate is centered such that capacitors that are in series have equal value. Those skilled in the art will appreciate that this justification of why the square shapes work when one set is rotated with respect to the other set does not limit the invention to square shaped top plates 18 and square shaped lower plates 14. These same sort of effect is obtained if (i) non-square shapes are used, (ii) non-uniform shapes are used with relative translation movement and (iii) shapes based on a polar coordinate system (like segmented rings of metal plates) are used with rotational movement.

The resonance frequency of the high impedance surface defines the frequency where the reflection phase crosses through zero. For a fixed test frequency, a change in the resonance frequency of the surface appears as a change in reflection phase. To measure the reflection phase of the experimental structure, a network analyzer was used and a pair of horn antennas,

one for transmitting and the other for receiving, were also used. The horns were placed next to each other, both aimed at the tunable surface, and separated by a sheet of microwave absorber. Microwave energy was transmitted from one horn, reflected by the surface, and received with the other horn, while the reflection phase was monitored for various positions of the movable board. The use of separate transmitting and receiving horns was used for this experiment because it eliminates interference from internal reflections within the antennas. The data was compared to a reference scan taken using a flat metal surface, which is known to have a reflection phase of π.

The reflection phase of the experimental structure is shown in Figure 17 as a function of frequency for ten different positions (numbered 1 through 10) of the upper board, displaced in the direction of the applied electric field. By varying the overlap area of the capacitor plates, the resonance frequency is tuned from roughly 1.7 GHz to 3.3 GHz. The series of scans shown corresponds to a total translation of one-half period of the textured surface, or 3.2 mm. The tuning range is limited by the maximum and minimum achievable capacitance, which depend on the area of the plates, the thickness of the insulator, and the fringing field in the surrounding medium.

b. Reflective Beam Steering

By varying the resonance frequency, and thus the reflection phase, as a function of position, the tunable surface can be used to steer a reflected beam. The simplest approach to beam steering is to create a monotonic, preferably linear phase gradient across the surface. For a mechanically tuned reflector, this can be accomplished by a rotation of one printed circuit board with respect to the other one, as shown in Figure 10. From the discussion set forth above, the reflection phase is only affected by translation of the capacitor plates in the direction parallel to the applied electric field. For a wave polarized along Y, only the component of translation in the Y direction is relevant, and the translation along X has no effect. For each individual capacitor plate, a small rotation of one board relative to the other produces a translation in Y that is roughly a linear function of X, but is largely independent of Y. Thus, rotation generates a monotonic phase gradient in the direction perpendicular to the applied electric field, which is equivalent to a virtual tilt of the surface. Only a small mechanical motion is required, since the maximum displacement needed at the edge of the board is only one-half of the lattice period.

To measure the beam steering properties of a tunable reflector afforded by the previously discussed experimental structure, the experimental structure was mounted vertically on a rotating pedestal and the reflection magnitude was measured as a function of incidence angle using two stationary horn antennas. Adjustment screws placed at two corners of the surface allowed

independent control of both the relative orientation and the relative vertical displacement of the two boards. Repeated measurements of the reflection pattern were taken for various positions of the movable board. The measurements described below were performed at 3.1 GHz.

With the plates 10, 20 of two boards 16, 18 of the experimental structure aligned with each other, the surface has no phase gradient, and the angle of reflection is equal to the angle of incidence. The reflection magnitude as a function of incidence angle is shown in Figure 19. As expected from the foregoing discussion, the reflection is strongest at 0 and 180 degrees when the front and back surfaces of the reflector are directly facing the horns. The lobes at other angles are due to reflections from the rotating stage, the edges of the boards, the adjustment screws, the walls of our anechoic chamber, and other objects. The asymmetry in the reflection magnitude and angular profile between the front and back sides of the pattern is due to an acrylic vacuum plate which was attached to the back of the reflector to hold the two printed circuit boards making up the experimental structure together. The difference in reflection phase between the two surfaces also contributes to this asymmetry, because it affects the way the reflected waves interfere with other reflections from the surroundings.

When one board of the experimental structure is rotated against the other, the resulting phase gradient causes a normally incident wave to be reflected at an angle given by $\theta = 2\tan^{-1}\left(\frac{\lambda g}{2\pi}\right)$,

where g is the phase gradient in radians per meter and λ is the wavelength. The reflection patterns for two different relative orientations of the plates 10, 20 of the two boards16,18 are shown in Figures 20a and 20b. Figures 20a and 20b are graphs of the measured reflection magnitude as a function of incidence angle with for two different relative orientations of the two boards. In Figure 20a the graph is for the orientation shown by Figure 18, while Figure 20b is for rotation of the upper board 18 in a direction opposite to that shown by Figure 18. The main lobes can be seen at angles of about ±8 degrees, indicating that the surface no longer reflects in the specular direction, but rather in a direction determined by magnitude and direction of the phase gradient. By rotating the upper surface between these extremes, the reflection angle can be tuned in an analog fashion. Of course, the lobe in the backward direction still appears at 180 degrees, because the back of the surface is untextured. It should be noted that because the transmitting and receiving horns are stationary and mounted next to each other, the main lobes of the reflection pattern indicate angles at which a plane wave is reflected directly back towards its source. This means that a normally incident plane wave would be reflected to twice the angle measured in this experiment, and could be steered over a range of ±16 degrees.

Because the resonance frequency is not a linear function of the displacement, as seen from Figure 17, the maximum useful range of motion is actually less than one-half period. For the results described above, the difference in displacement between the two edges of the structure was roughly 1 mm, or 0.01 wavelength. The higher-frequency region is preferred between 2.5 GHz and 3.3 GHz, where the resonance frequency is roughly a linear function of displacement. This region also defines the bandwidth over which the surface can effectively steer a beam.

c. Microwave Grating

Using a monotonic phase function, the maximum reflection angle is achieved when the phase varies by 2π across the width of the surface. This limits the beam steering capabilities of a surface with a width w to $\theta = 2\tan^{-1}\left(\frac{w}{\lambda}\right)$. In order to steer to larger angles, a larger phase gradient must be used. Since phase can only be defined modulo 2π, periodic discontinuities of 2π must be included in the phase function. Such a surface can effectively be considered a grating. Generally speaking, gratings are physical structures. In this embodiment the present invention mimics a grating.

In order to test a microwave grating with two periods using the experimental structure, the movable board 18 was physically divided down its center into two portions 18a and 18b, and the two portions were offset as shown in Figure 21. This provided the phase discontinuity used to produce a two-period grating, which has twice the phase gradient as the monotonic surface previously described. As can be seen from Figures 22a and 22b. Figures 22a and 22b are graphs of the measured reflection magnitude as a function of incidence angle with for two different relative orientations of the two boards when set up to have two periods as shown in Figure 21. In Figure 22a the graph is for the orientation shown by Figure 21, while Figure 22b is for rotation of the upper board 18 in a direction opposite to that shown by Figure 21. The maximum reflection angle now occurs at ±19 degrees. For a normally incident plane wave this corresponds to beam steering of ±38 degrees. As before, the beam could be steered to any angle within this range by adjusting the phase gradient, while maintaining the 2π phase discontinuity. For larger angles, or for larger surfaces, multiple discontinuities can of course be used.

The patterns shown for this experiment exhibit scattering at other angles. This is because rotation of the upper board of the experimental structure does not produce a perfectly linear phase function, as dictated by the functional dependence of the resonance frequency on the

displacement of the capacitor plates. The problem is most severe at the phase discontinuities, as shown in Figure 23. With more accurate control over the resonance frequency of each individual cavity, the pattern could be improved.

While the phase function produced by this rotational motion tends to be nonlinear, it can be close enough to linear to produce a well-formed beam, as seen in the data. Moreover, it may well be possible to compensate for this non-linearity, and one way of doing this could be to adjust the spacing of the cells C_1 - C_4 formed by plates 10, 20. Another approach would be to adjust the size of the cells C_1 - C_4, while keeping the spacing of the plates uniform. The main objective of this approach would be to provide a surface in which the capacitance is decreased more slowly near the edge on which it is being decreased the most – in other words, to cancel the non-linearity of the phase function. One example of a structure that could do this is shown by Figure 24. The plates 20 are made longer and narrower on one side, but shorter and wider on the other side. The total capacitance is the same, and but the side with the longer and narrower squares will be slightly less sensitive to translation in the vertical direction. Rotation, as represented by arrow 27, around pivot point 25 should produce a more linear phase function than a uniform lattice would produce. This technique could be used to make any other phase function desired.

In the embodiments shown by the drawings the tunable impedance surface is depicted as being planar. However, the invention is not limited to planar tunable impedance surfaces. Indeed, those skilled in the art will appreciate the fact that the printed circuit board technology preferably used to provide substrates 16, 18 for the tunable impedance surface can provide a very flexible substrate. Thus, the tunable impedance surface can be mounted on any convenient surface and conform to the shape of that surface. However, a planar configuration is preferred since that should make it easier to move board 18 relative to board 16 when the surface it tuned.

The top plate elements10 and the ground or back plane element 12 are preferably formed from a metal such as copper or a copper alloy conveniently used in printed circuit board technologies. However, non-metallic, conductive materials may be used instead of metals for the top plate elements 10 and/or the ground or back plane element 12, if desired. This is also true for plates 20 formed on board 18.

Having described the invention in connection with certain embodiments thereof, modification will now certainly suggest itself to those skilled in the art. As such, the invention is not to be limited to the disclosed embodiments except as required by the appended claims.

CLAIMS:

1. A tuneable impedance surface for reflecting a radio frequency beam, the tunable surface comprising:

(a) a ground plane;

(b) a plurality of elements disposed in an array a distance from the ground plane, the distance being less than a wavelength of the radio frequency beam; and

(c) a capacitor arrangement for controllably varying capacitance between at least selected ones of adjacent elements in said array.

2. The tuneable impedance surface of claim 1 wherein the capacitor arrangement comprises a an array of discrete variable capacitance elements associated with the elements disposed in the first mentioned array.

3. The tuneable impedance surface of claim 1 wherein the capacitor arrangement includes a plurality of microelectomechanical capacitors connected between adjacent elements.

4. The tuneable impedance surface of claim 1 wherein the capacitor arrangement includes a plurality of variacs connected between adjacent elements.

5. The tuneable impedance surface of any one of claims 1 - 4 wherein approximately one-half of the elements are directly or ohmically coupled to the ground plane by vias in a substrate supporting said ground plane, said plurality of elements and said capacitor arrangement.

6. The tuneable impedance surface of claim 5 wherein the elements which are not directly or ohmically coupled to the ground plane are coupled to a data bus for applying control voltages thereto.

7. The tuneable impedance surface of claim 6 wherein the elements, which are coupled to the data bus, are also capacitively coupled to the ground plane so as to appear to effectively shorted thereto for a frequency or frequencies of said radio frequency beam.

8. The tuneable impedance surface of any one of claims 1 - 4 wherein less than one-half of the elements are directly or ohmically coupled to the ground plane.

9. The tuneable impedance surface of claim 8 wherein more than one-half of the elements

are coupled to a data bus for applying control voltages thereto.

10. The tuneable impedance surface of any one of claims 6 - 8 wherein the elements which are coupled to the data bus are capacitively coupled to the ground plane so as to appear to effectively shorted thereto for a frequency or frequencies of said radio frequency beam.

11. The tuneable impedance surface of claim 10 wherein all of the elements are coupled to a data bus for applying control voltages thereto.

12. The tuneable impedance surface of claim 11 wherein the elements are capacitively coupled to the ground plane so as to appear to effectively shorted thereto for a frequency or frequencies of said radio frequency beam.

13. The tuneable impedance surface of claim 1 wherein the capacitor arrangement comprises a second plurality of elements disposed in an array a second distance from the ground plane, the second plurality of elements be moveable relative to the first plurality of elements.

14. The tuneable impedance surface of claim 13 wherein the first plurality of elements and the second plurality of elements are arranged in parallel planar arrays.

15. The tuneable impedance surface of claims 13 or 14 wherein the first plurality of elements and the second plurality of elements are separated by a dielectric layer.

16. The tuneable impedance surface of claim 15 wherein the first plurality of elements and the second plurality of elements abut said dielectric layer.

17. The tuneable impedance surface of claims 15 or 16 wherein the first plurality of elements are fixed relative to said dielectric layer and the second plurality of elements a moveable relative to said dielectric layer.

18. The tuneable impedance surface of any one of the preceding claims further including a substrate having first and second major surfaces, said substrate supporting said ground plane on the first major surface thereof and supporting said plurality of elements on the second major surface thereof.

19. The tuneable impedance surface of any one of the preceding claims wherein said capacitor arrangement is adjustable to spatially tune the impedances of said plurality of

elements.

20. The tuneable impedance surface of any one of the preceding claims wherein the plurality of elements each have an outside diameter which is less than the wavelength of the radio frequency beam.

21. The tuneable impedance surface of any one of the preceding claims wherein the capacitor arrangement controllably varies the capacitance between all adjacent elements.

22. A method of tuning a high impedance surface for reflecting a radio frequency signal comprising:

arranging a plurality of generally spaced-apart conductive surfaces in an array disposed essentially parallel to and spaced from a conductive back plane, and

varying the capacitance between at least selected ones of adjacent conductive surfaces in said array to thereby tune the impedance of said high impedance surface.

23. The method of claim 22 wherein the step varying the capacitance between adjacent conductive surfaces in said array includes connecting microelectomechanical capacitors between said at least selected ones of adjacent conductive surfaces.

24. The method of claim 22 or 23 wherein the step of varying the capacitance between at least selected ones of adjacent conductive surfaces includes applied control voltages to at least selected ones of said conductive surfaces.

25. The method of any one of claims 22 - 24 wherein the size of each conductive surface along a major axis thereof is less than a wavelength of the radio frequency signal, and preferably less than one tenth of a wavelength of the radio frequency signal, and the spacing of each conductive surface from the back plane being less than a wavelength of the radio frequency signal.

26. The method any one of claims 22 - 25 wherein the high impedance surface is tuned so that a parabolic reflection phase function is impressed on the high impedance surface.

27. The method of claim 26 wherein the parabolic phase function has discontinuities of 2π therein.

28. The method of any one of claims 22 - 25 wherein the high impedance surface is tuned

so that a linear reflection phase function is impressed on the high impedance surface.

29. The method of claim 28 wherein the linear phase function has discontinuities of 2π therein.

30. The method of any one of claims 22 - 25 wherein the conductive surfaces are generally planar and wherein the array is generally planar.

31. The method of claim 22 wherein the step of varying the capacitance between at least selected ones of adjacent conductive surfaces in the first mentioned array includes:

arranging a second plurality of generally spaced-apart conductive surfaces in a second array disposed essentially parallel to and spaced from said conductive back plane by a distance greater than the distance said first plurality of generally spaced-apart conductive surfaces is spaced from said conductive back plane, and

moving the second plurality of generally spaced-apart conductive surfaces relative to the first plurality of generally spaced-apart conductive surfaces.

32. The method of claim 31 wherein the step of moving the second plurality of generally spaced-apart conductive surfaces relative to the first plurality of generally spaced-apart conductive surfaces comprises rotational movement in a plane essentially parallel to said arrays.

33. The method of claim 31 or 32 wherein the size of each conductive surface along a major axis thereof is less than a wavelength of the radio frequency signal, and preferably less than one tenth of a wavelength of the radio frequency signal, and the spacing of each conductive surface of the first plurality from the back plane is less than a wavelength of the radio frequency signal.

34. The method of any one of claims 31 - 33 wherein the high impedance surface is tuned so that a linear reflection phase function is impressed on the high impedance surface.

35. The method of claim 34 wherein the linear phase function has discontinuities of 2π therein.

36. The method of any one of claims 22 - 35 wherein the conductive surfaces are generally planar and wherein the array is generally planar.

37. The method of any one of claims 22 - 36 wherein the capacitance is varied between all adjacent elements.

38. The method of any one of claims 22 - 37 wherein the high impedance surface steers and/or focusses said radio frequency signal .

39. A tuneable impedance surface for reflecting a radio frequency beam, the tunable surface comprising:

(a) a first substrate formed of a dielectric material having a thickness which is less than a wavelength of the radio frequency beam;

(b) a conductive back plane disposed on a first major surface of said first substrate;

(c) a first plurality of elements disposed in an array on a second major surface of said first substrate, each element of said first plurality of elements having an outside dimension which is less than a wavelength of the radio frequency beam;

(d) a second substrate formed of a dielectric material having a thickness which is less than a wavelength of the radio frequency beam, then second substrate being disposed in a confronting relationship to the first substrate;

(e) a second plurality of elements disposed in an array on said second substrate, each element of the second plurality of elements having an outside dimension which is less than a wavelength of the radio frequency beam; and

(f) the second substrate being moveable laterally relative to the first substrate for controllably varying the impedance of said tuneable impedance surface.

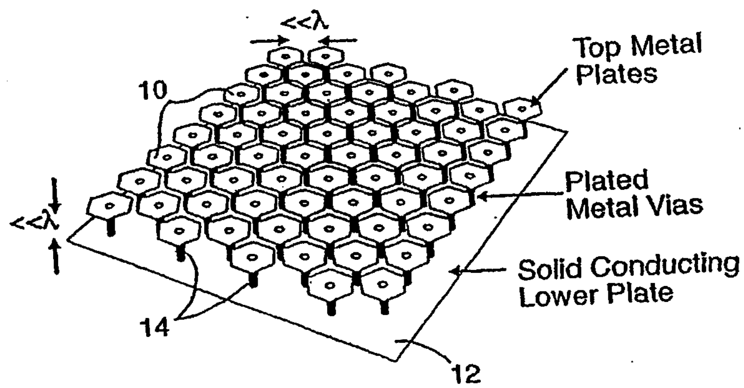

Figure 1

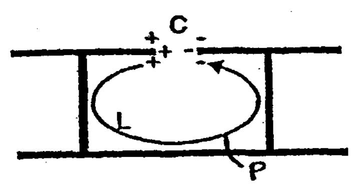

Figure 2

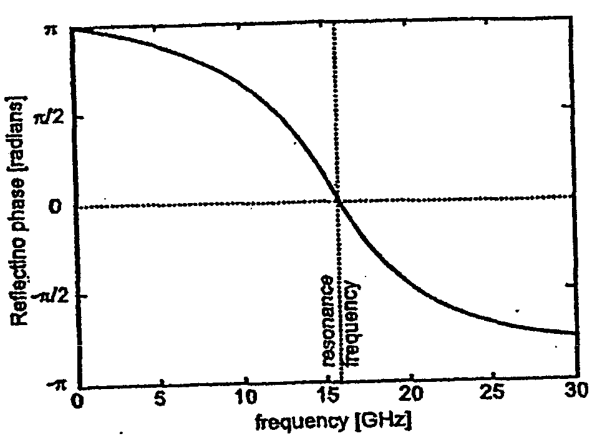

Figure 3

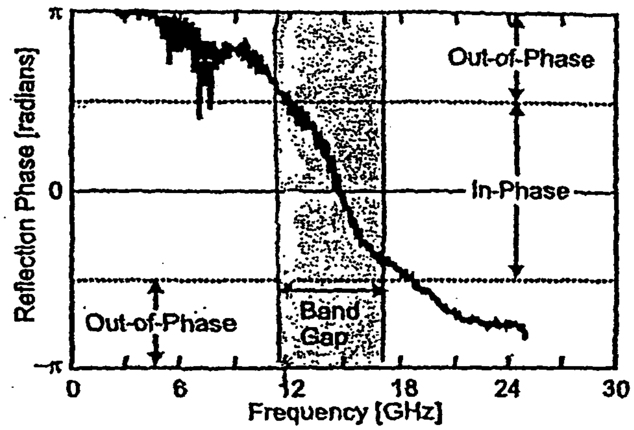

Figure 4

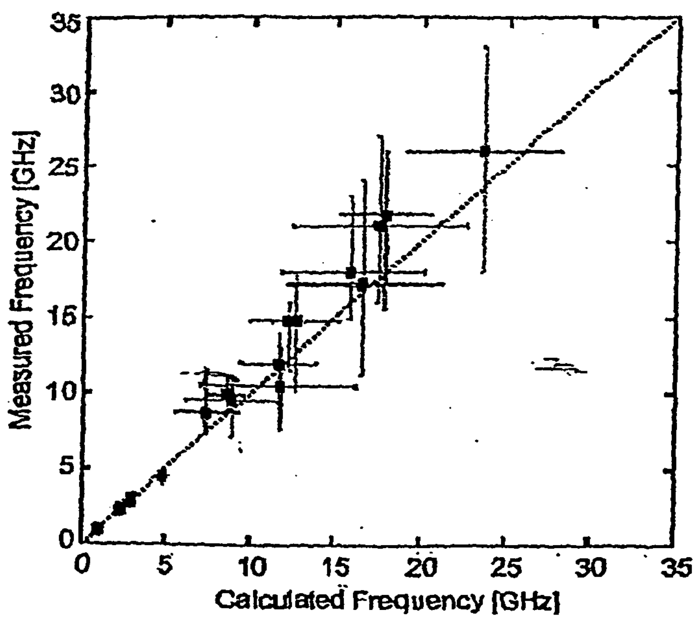

Figure 5

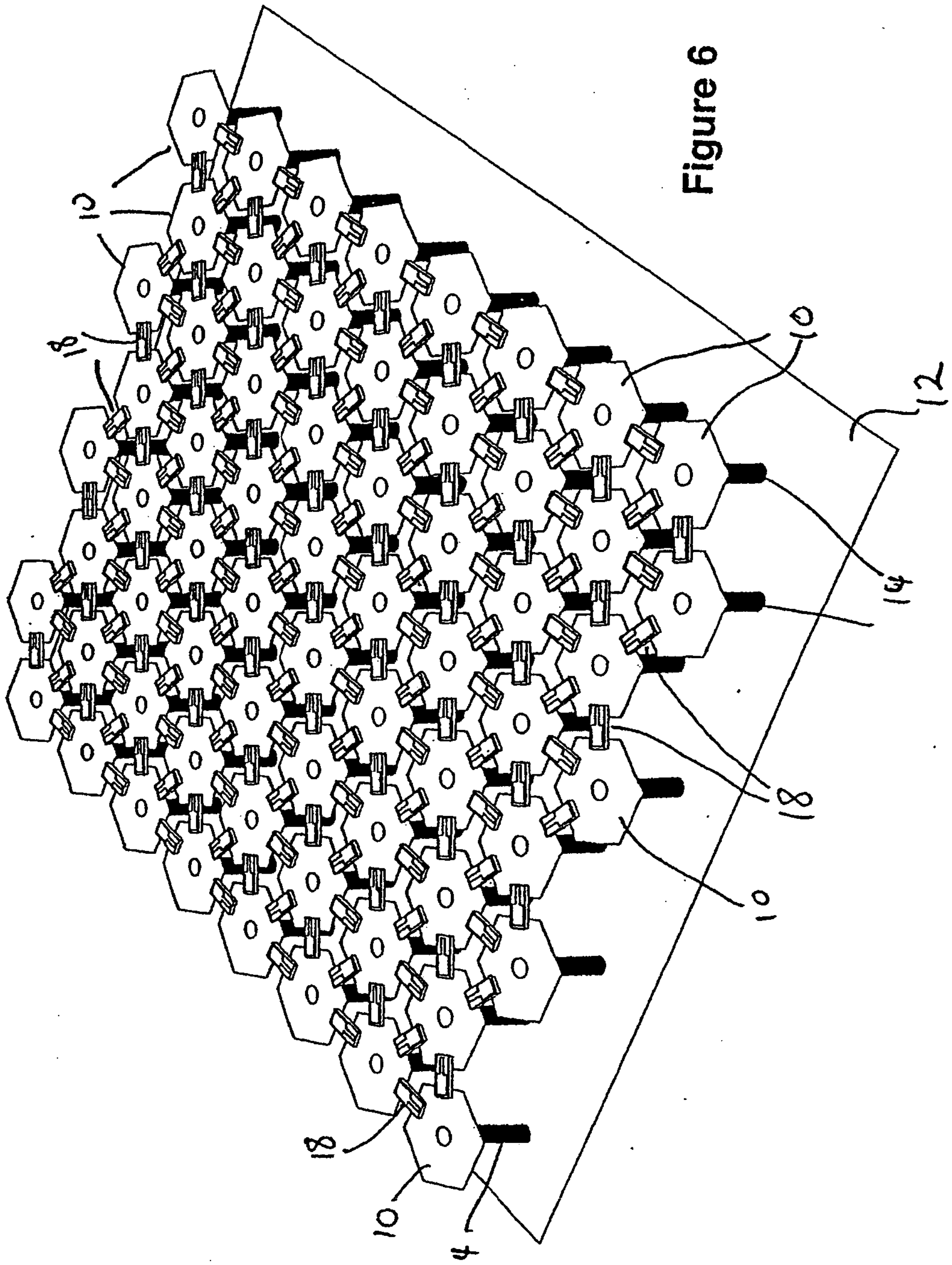

Figure 6

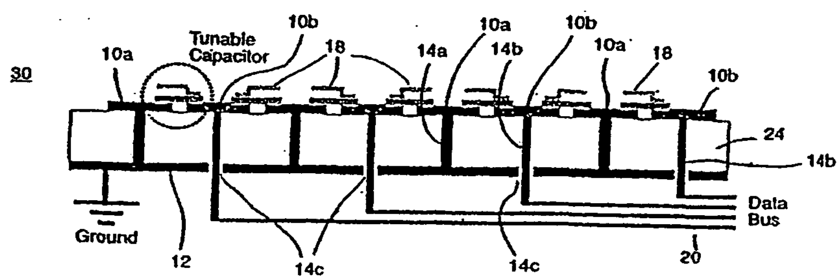

Figure 7

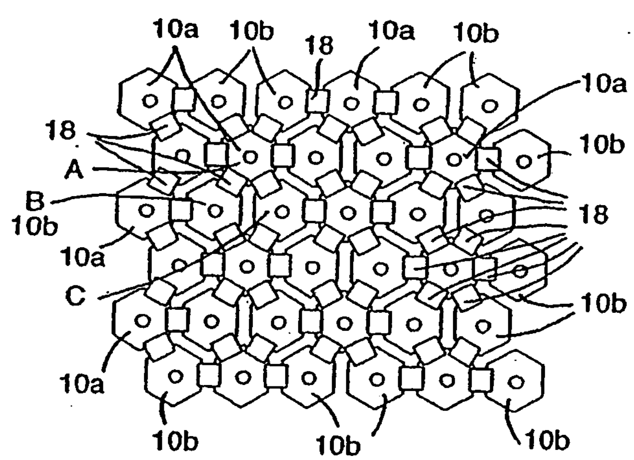

Figure 8

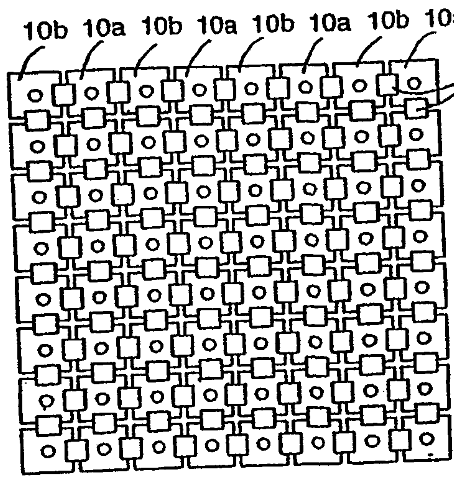

Figure 9

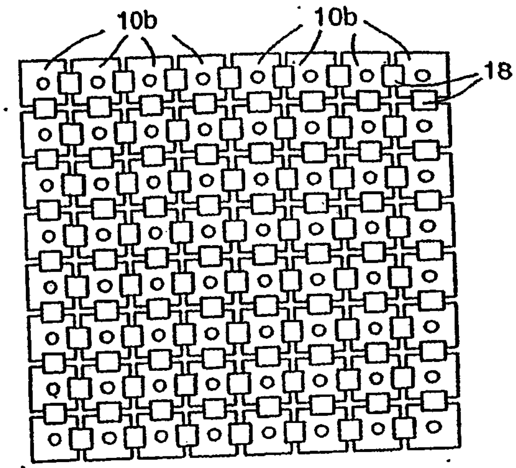

Figure 9a

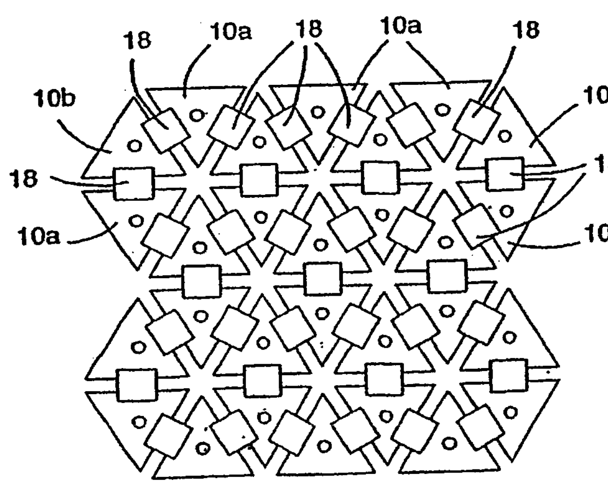

Figure 10

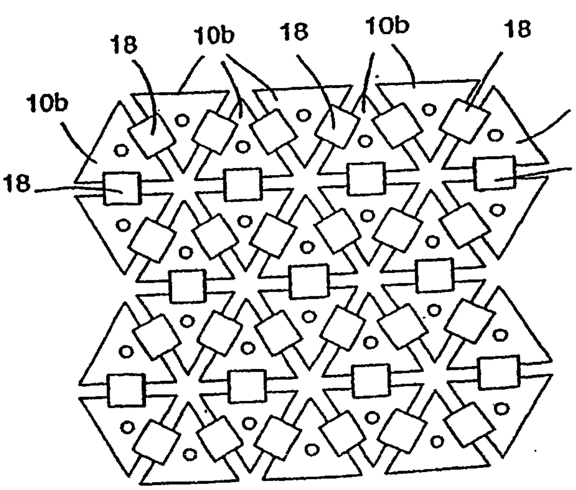

Figure 10a

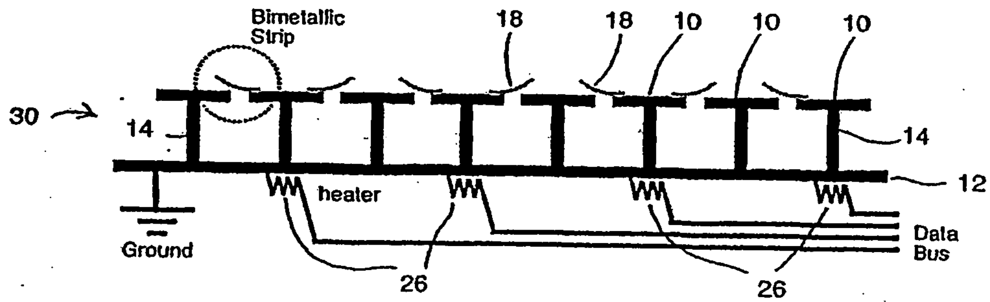

Figure 11

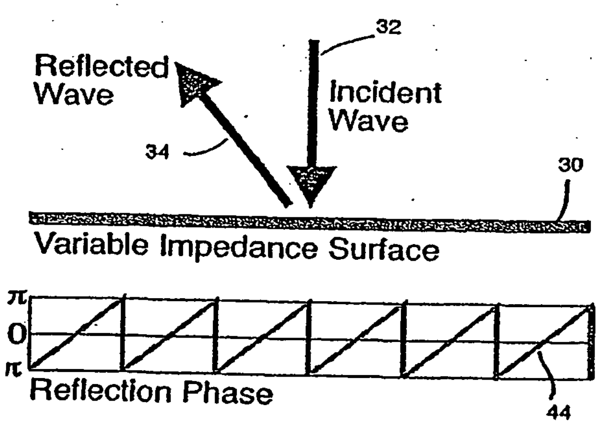

Figure 12

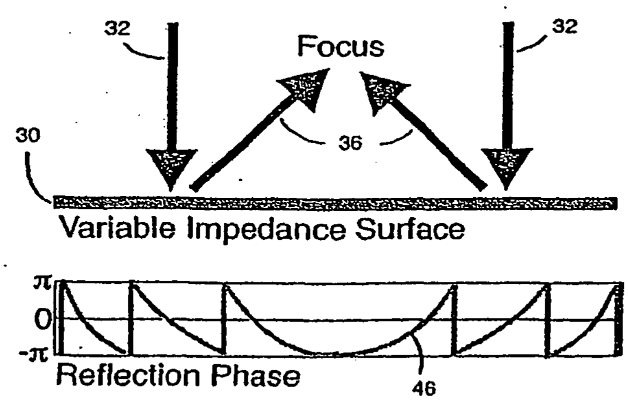

Figure 13

Figure 14b

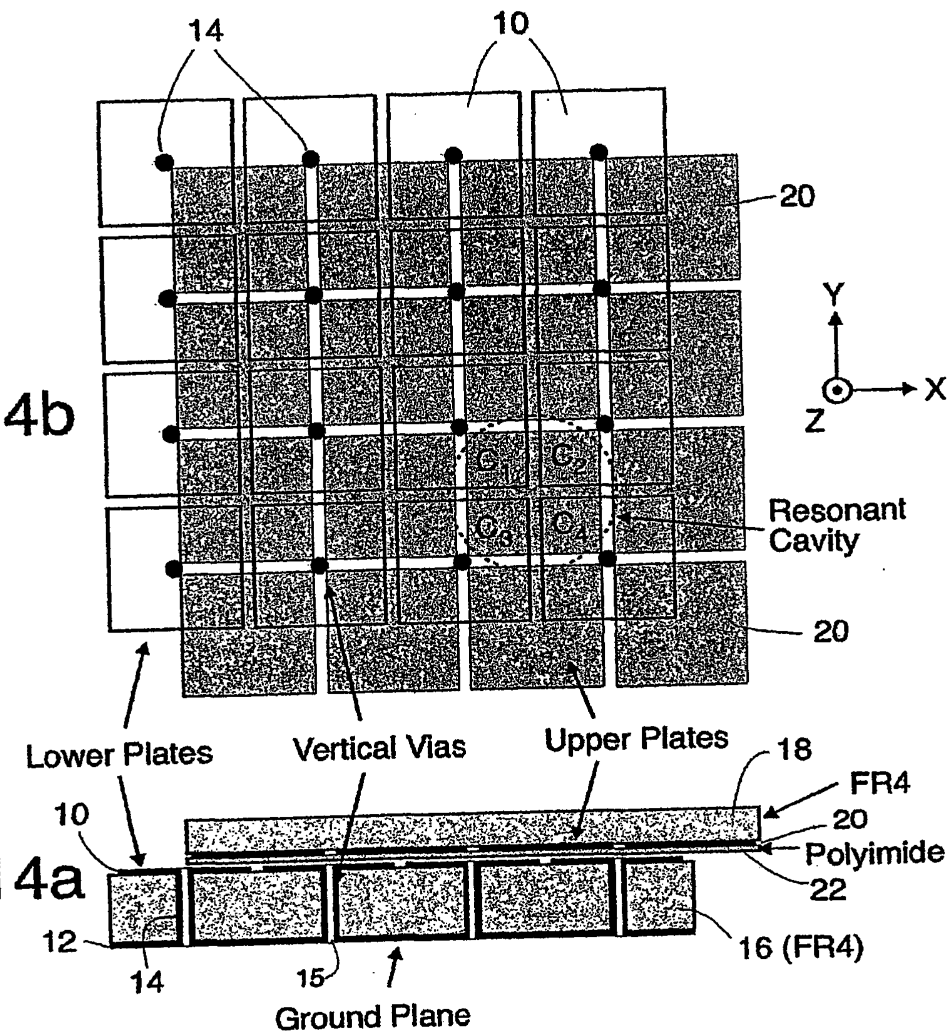

Figure 14a

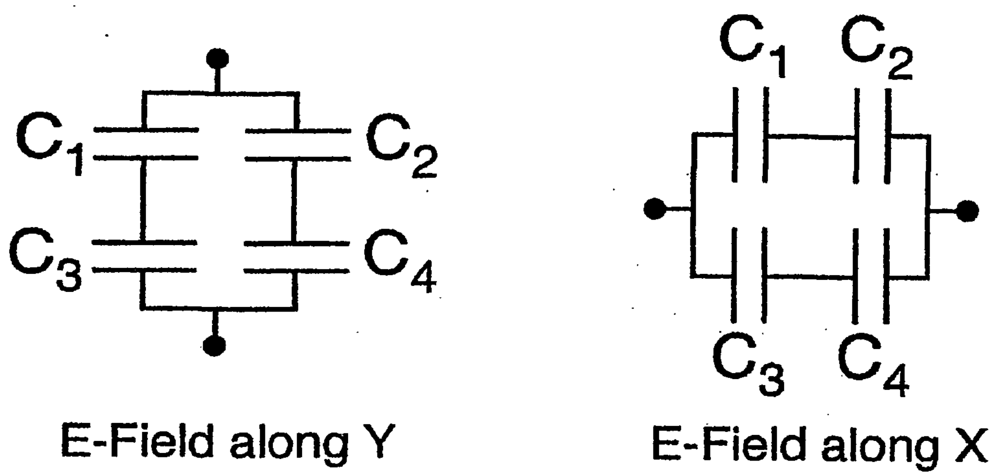

Figure 15

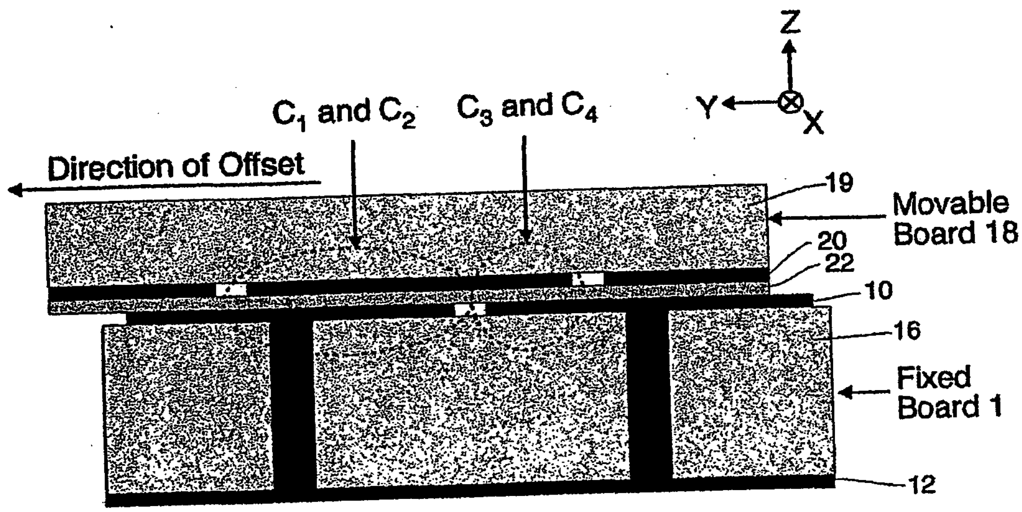
Z
Y
X
C_1 and C_2
C_3 and C_4
Direction of Offset
19
Movable Board 18
20
22
10
16
Fixed Board 1
12

Figure 16

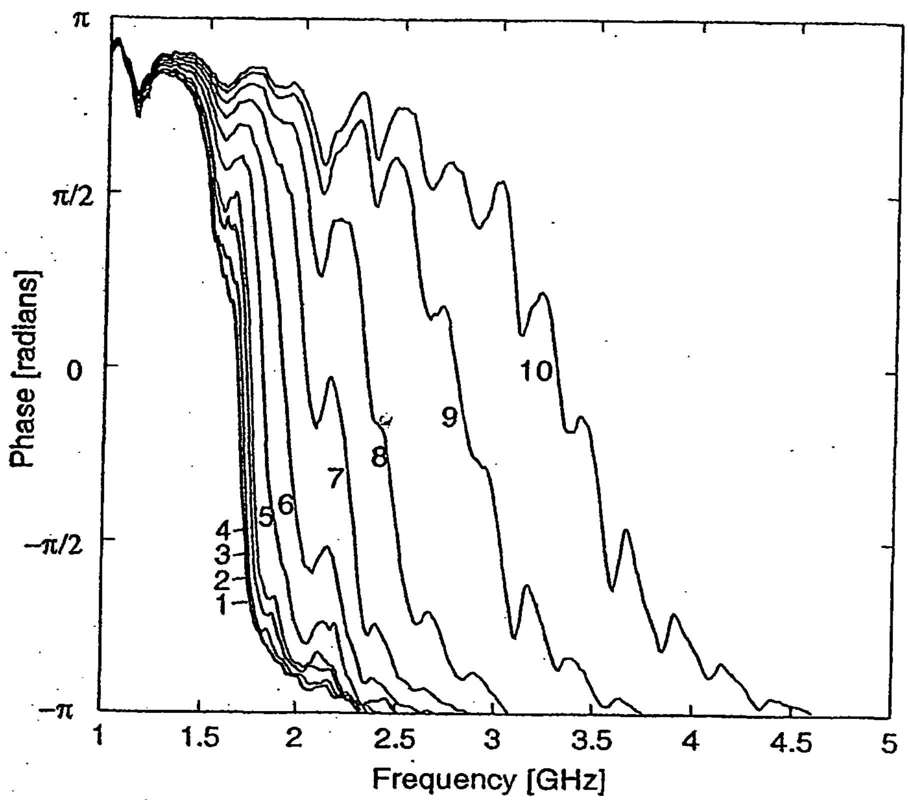
π
π/2
0
−π/2
−π
Phase [radians]
1
1.5
2
2.5
3
3.5
4
4.5
5
Frequency [GHz]
1
2
3
4
5
6
7
8
9
10

Figure 17

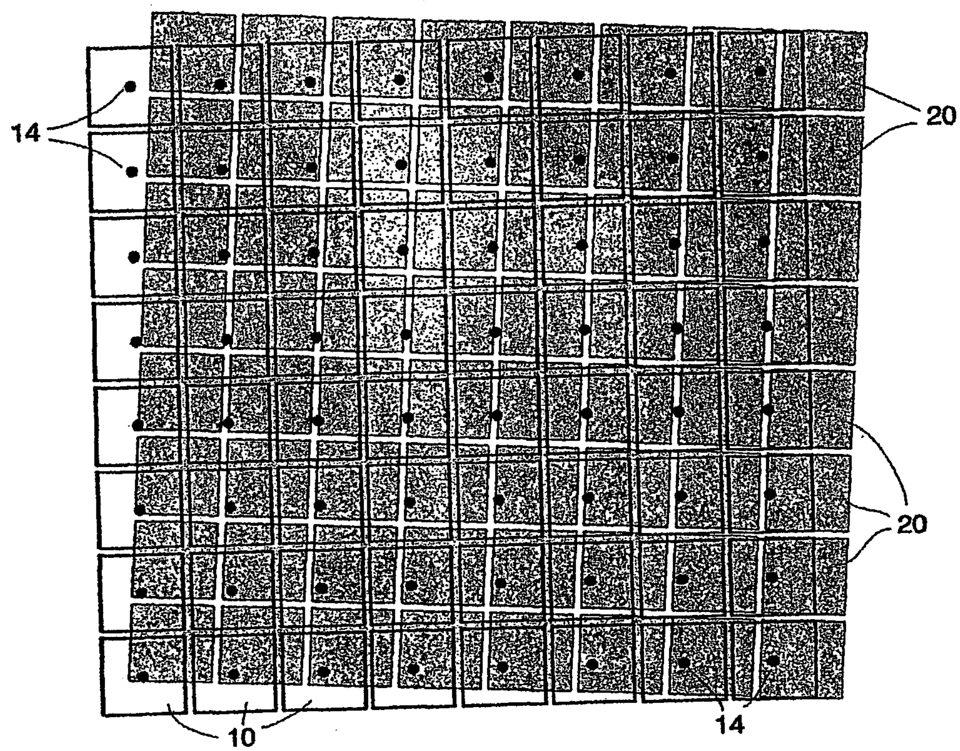

Figure 18

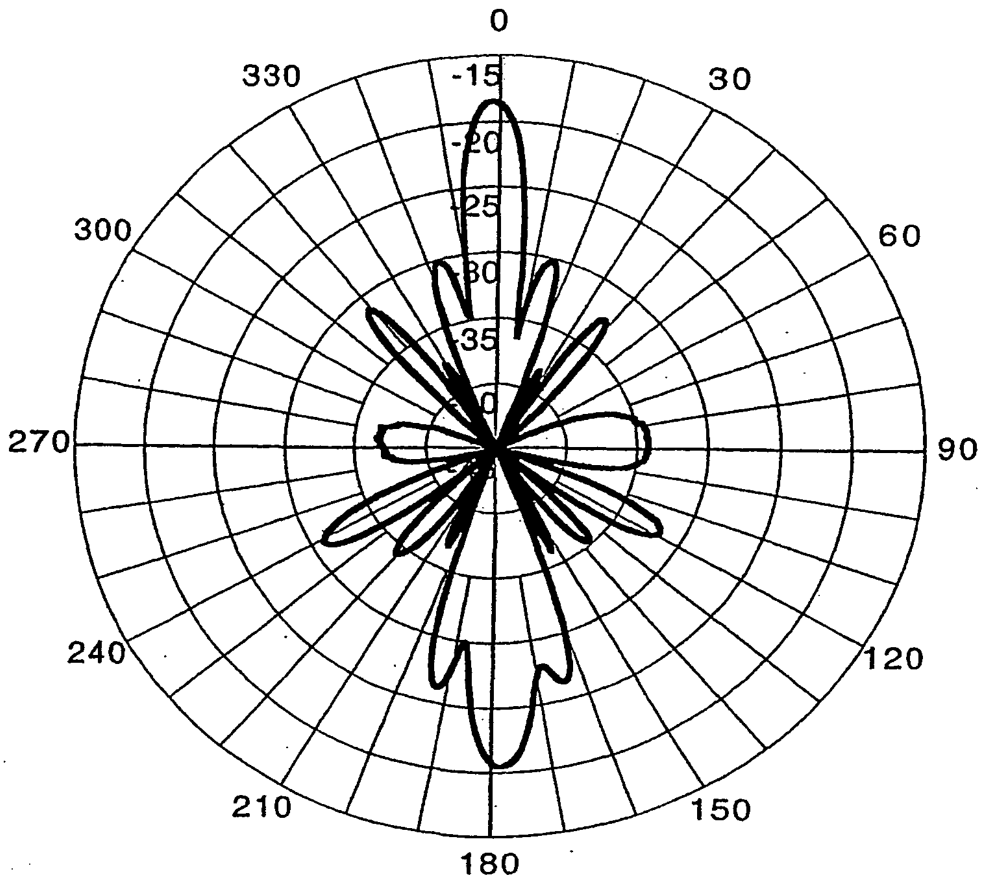

Figure 19

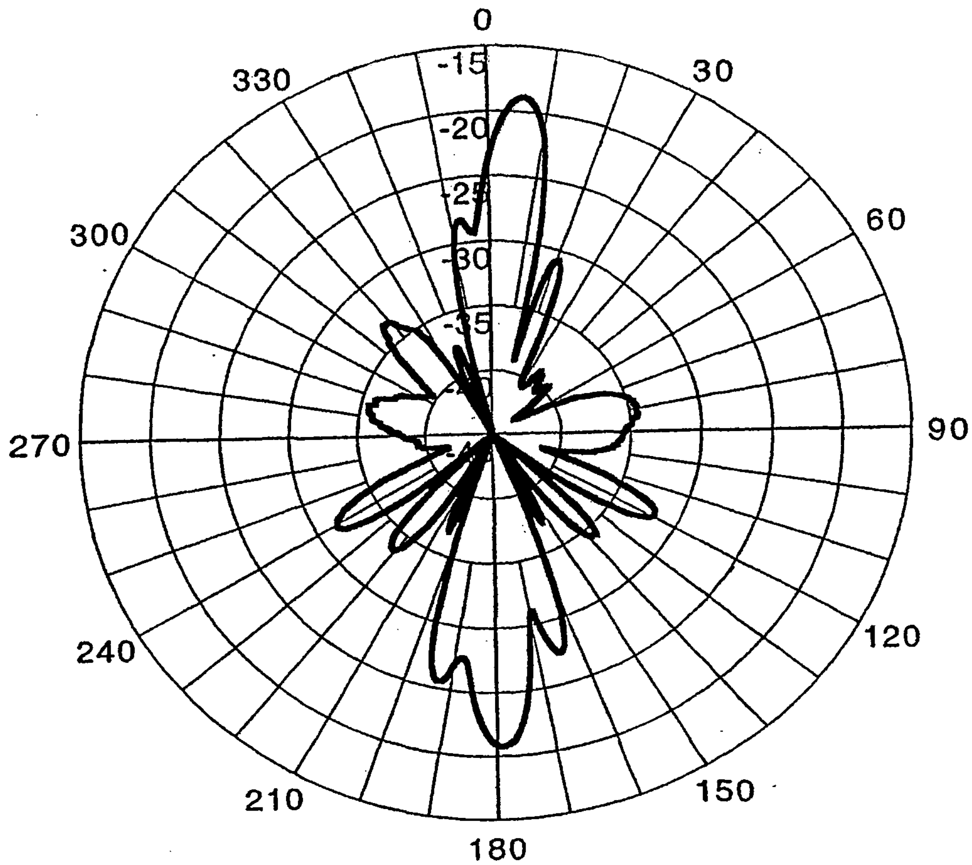

Figure 20a

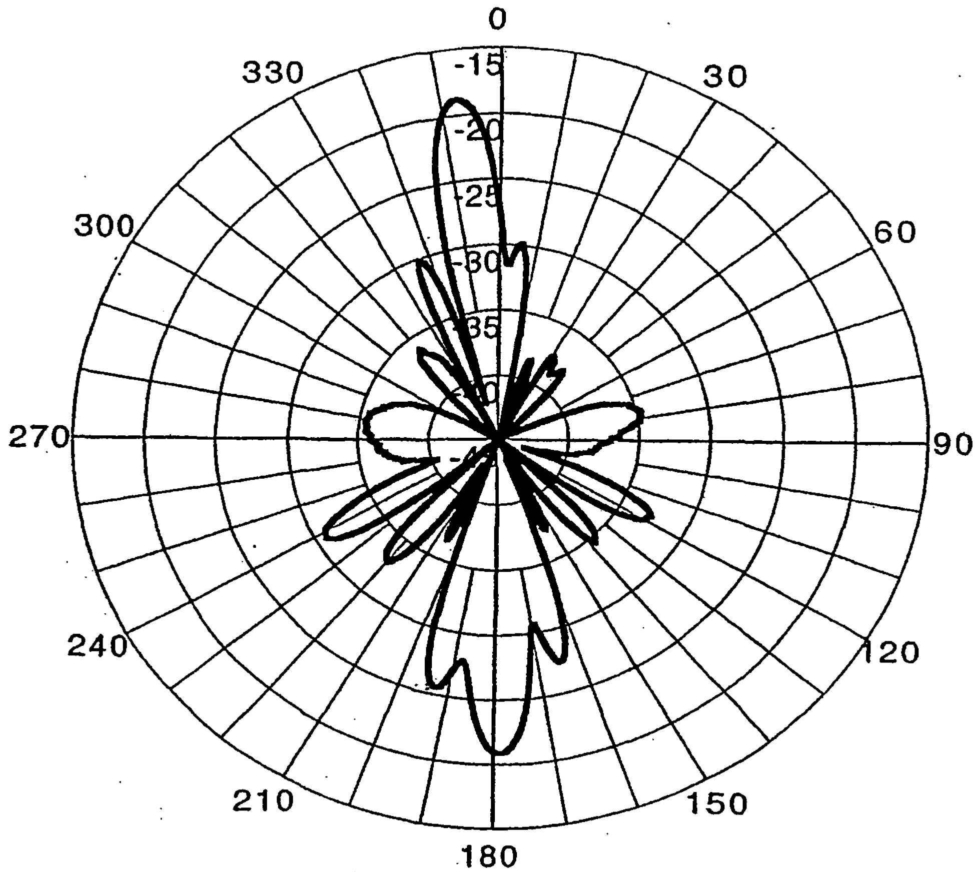

Figure 20b

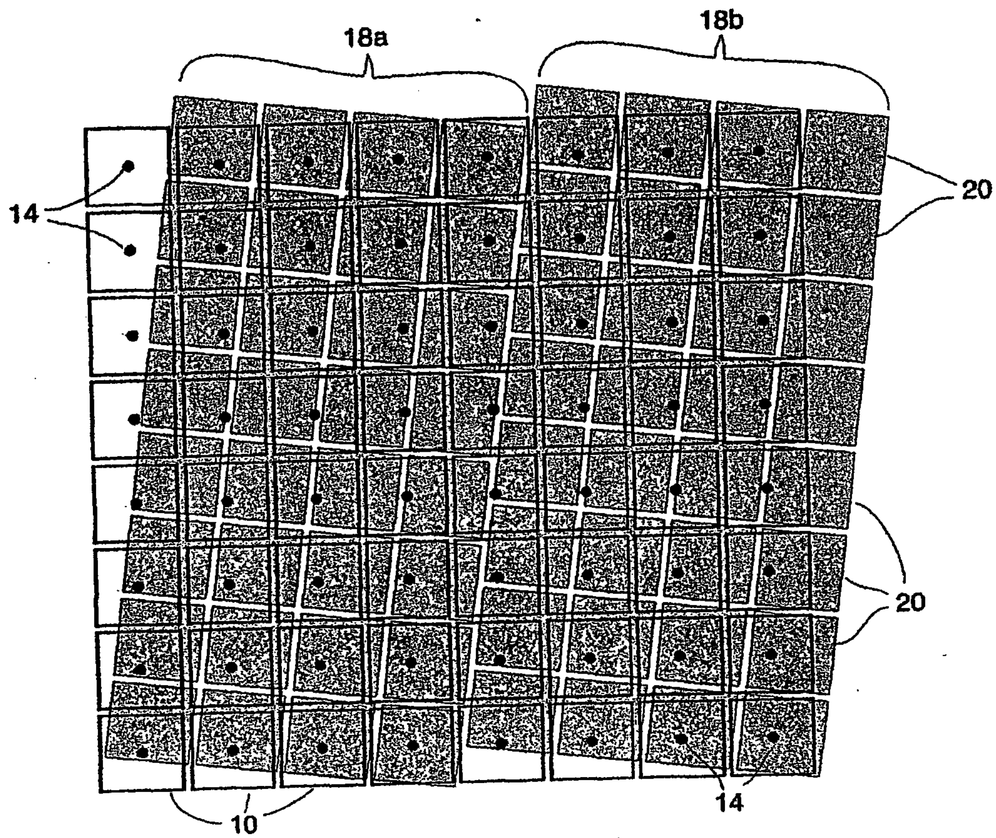

Figure 21

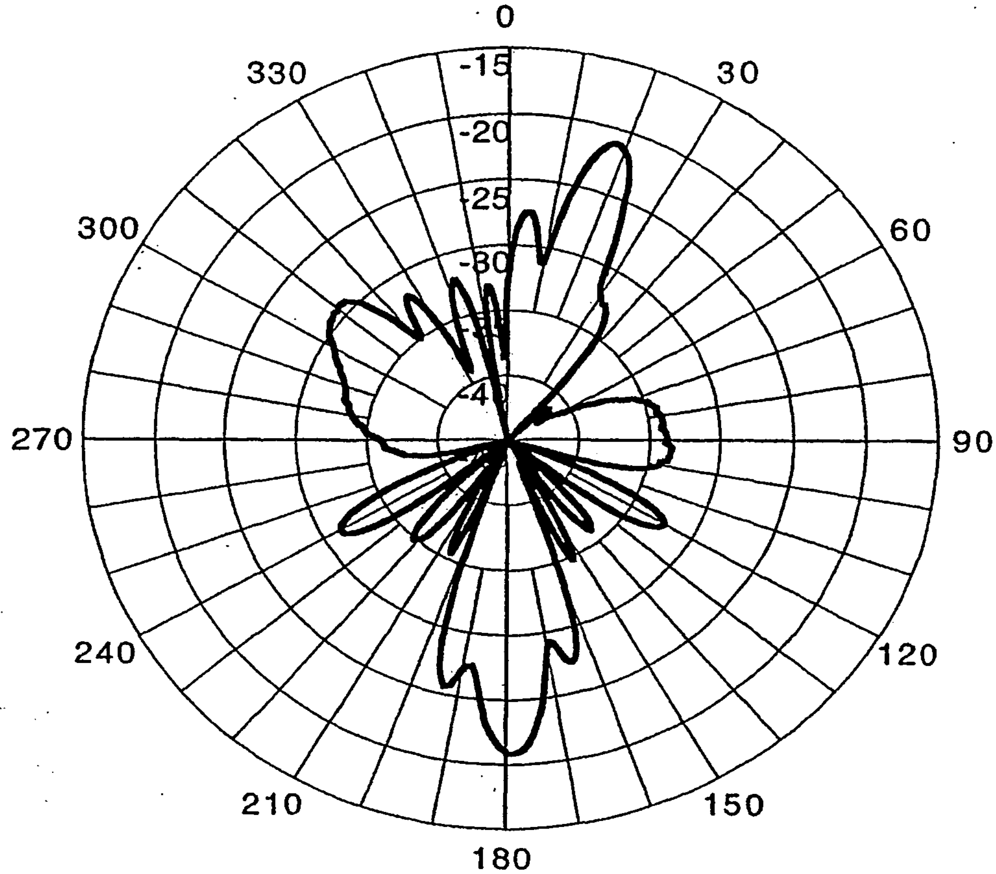

Figure 22a

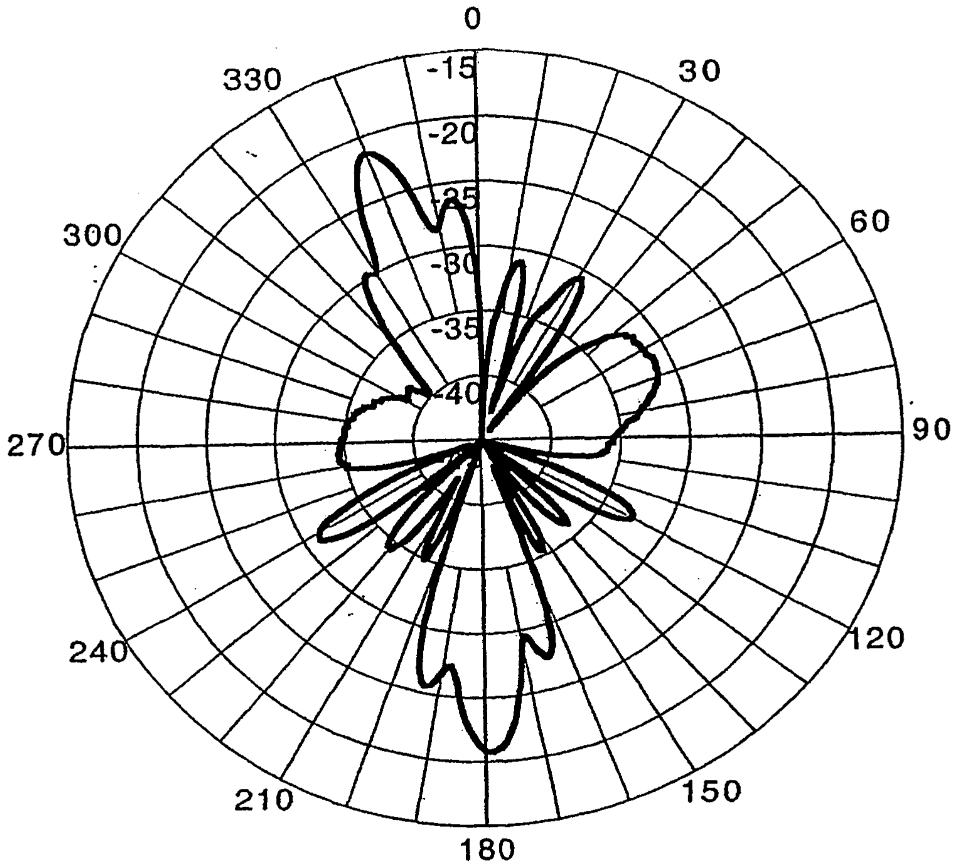

Figure 22b

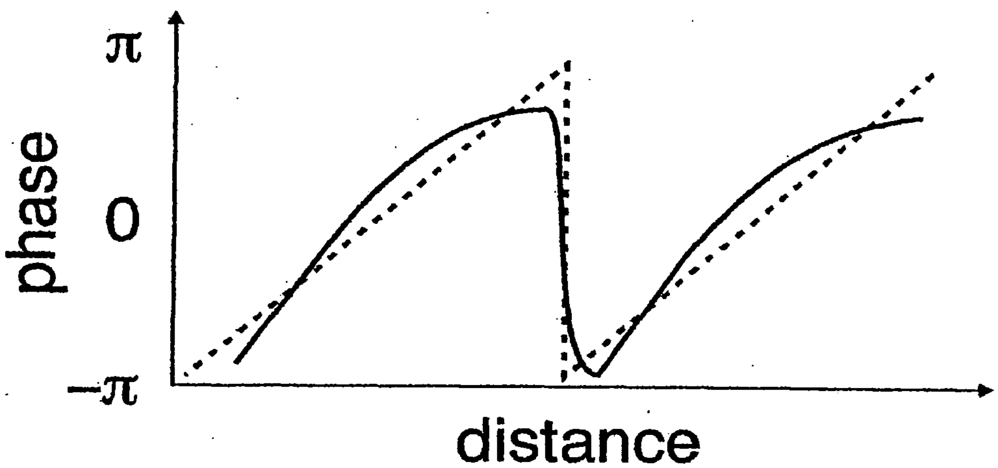

Figure 23

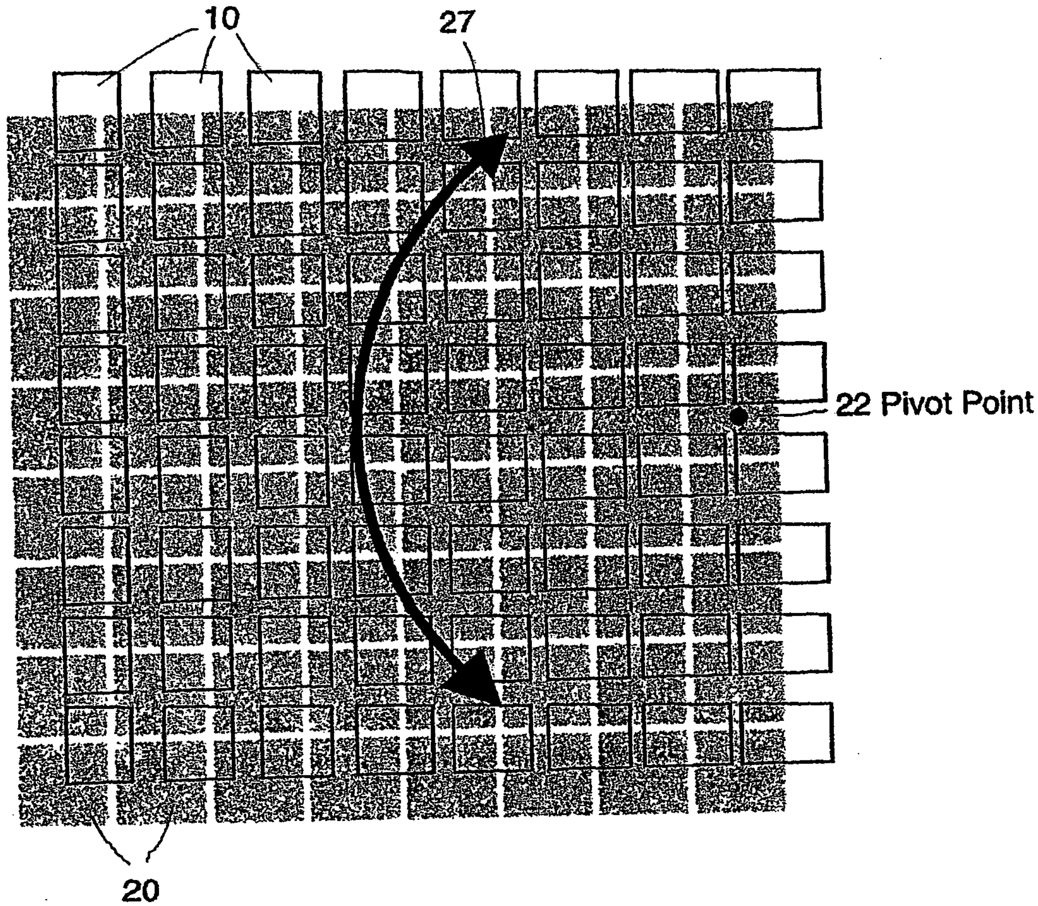

Figure 24

INTERNATIONAL SEARCH REPORT

International Application No
PCT/US 01/09973

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 H01Q15/00 H01Q9/04

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7 H01Q

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

PAJ, WPI Data, EPO-Internal

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	EP 0 539 297 A (COMMISSARIAT ENERGIE ATOMIQUE) 28 April 1993 (1993-04-28) the whole document ---	1-39
A	SIEVENPIPER D ET AL: "ELIMINATING SURFACE CURRENTS WITH METALLODIELECTRIC PHOTONIC CRYSTALS" 1998 IEEE MTT-S INTERNATIONAL MICROWAVE SYMPOSIUM DIGEST. IMS '98. PROGRESS THROUGH MICROWAVES. BALTIMORE, MD, JUNE 7 - 12, 1998, IEEE MTT-S INTERNATIONAL MICROWAVE SYMPOSIUM DIGEST, NEW YORK, NY: IEEE, US, vol. 2, 7 June 1998 (1998-06-07), pages 663-666, XP000822079 ISBN: 0-7803-4472-3 the whole document --- -/--	1-39

[X] Further documents are listed in the continuation of box C.

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10 August 2001	21/08/2001

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C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT		
Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 5 021 795 A (MASIULIS) 4 June 1991 (1991-06-04) the whole document ---	1-38
A	WO 99 50929 A (SIEVENPIPER DAN ;UNIV CALIFORNIA (US); YABLONOVITCH ELI (US)) 7 October 1999 (1999-10-07) page 18, line 19 -page 19, line 3; figures 14A,14B -----	1-38

INTERNATIONAL SEARCH REPORT

Information on patent family members

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